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The Interaction of Small and Large Spacecraft with Their Environment

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Abstract: The most significant results from small scientific satellites and from the space shuttle mission STS-3 regarding body-plasma interactions are presented and discussed. The causes for the above information being meagre and fragmentary are given. The research avenues to be followed in the future in order to correct this situation are mentioned, including practical ways to achieve this goal.

1. GENERAL BACKGROUND

The interaction of a spacecraft (satellite, space shuttle, space station) with its environmental space plasma is a fundamental area of research in space plasma physics and in planetary geophysics. The interest in this area stems from both the science and application points of view.

From the general scientific point of view, we are dealing with the complex of phenomena and physical processes involved in the "electrodynamic interaction between an obstacle and its environmental rarefied plasma." Examples of such interactions in the solar system are the interactions between:

(1) Self-magnetized bodies such as the Earth, Jupiter, Saturn, Mercury, and Uranus with the solar wind.

(2) Non-magnetized bodies such as our moon and the moons of the large planets (e.g., Io and Titan) with the solar wind and/or with the magnetospheres of their parent planets (Jupiter and Saturn).

(3) Comets and the solar wind.

(4) Planetary ionospheres with the solar wind (e.g., Venus).

(5) Artificial bodies, i.e., small and large spacecraft with planetary ionospheres, magnetospheres, and the solar wind.

There are significant differences between the various interactions mentioned, but there also exist fundamental points of similarity. Hence, there can be no doubt that investigating "body-plasma interactions" under a wide range of plasma and body parameters will lead eventually to a UNIFIED approach in dealing with such interactions.

The interaction between a "body" and its surrounding plasma is MUTUAL. That is, both body and plasma are affected. The effects on the body result mainly in the charging of its surface, whereas the effects on the plasma result in the creation of shocks ahead of the body and very complicated wakes behind the body.

In addition to the scientific interest in understanding the complex phenomena and the relevant physical processes involved in the body-plasma interaction, there is also the practical aspect which is relevant to: (1) reliability, quality and the correct interpretation of low-energy particle and field measurements performed by probes mounted onboard satellites, (2) the optimal design of probes and their location on satellite surfaces and/or on booms. The latter aspect is of course essential for future space missions.

In the present paper we limit our discussion to the interaction of spacecraft, small and large, with their environmental ionospheric-plasmaspheric plasmas. Namely, our discussion is limited to the interaction of artificial non-magnetized bodies with a collisionless space plasma. The most significant results obtained from in situ measurements made by probes mounted on small scientific satellites and results obtained from some space shuttle missions will be presented and discussed. Within this framework we focus on the wake region and particularly on the variations of the [wake/ram] current ratio with several body and plasma parameters. We do not discuss spacecraft charging. Comprehensive reviews regarding spacecraft charging are given in Garrett, 1981; Whipple, 1981; Grard et al., 1983. Hence, we limit the discussion to one group of body-plasma interaction phenomena; i.e., effects on the plasma in the vicinity of artificial satellites. This limited group of body-plasma interactions, can further be classified to interactions based on the surface properties of the bodies; i.e., interactions which depend mainly on the degree of electrical conductivity.

It is possible to classify the interactions according to increasing/decreasing body-size or classify the interactions based on the specific plasma flow regime where the interaction takes place. For example, the interaction between the space-station and its ionospheric environment is a case of an interaction between a "large body" having, most likely, a relatively poor conducting surface, with a supersonic and sub-Alfvénic collisionless plasma. The interactions between a standard scientific satellite with the ionosphere, is a case of the interaction of a "small/medium" conducting body in a supersonic/hypersonic flow regime whereas the interaction between a spacecraft orbiting at plasmaspheric and magnetospheric altitudes takes place in a subsonic/transonic flow regime. It should be noted that a satellite orbiting the earth with a low altitude perigee and a high altitude apogee may go through several types of body-plasma interactions every orbit.

It should be noted that in dealing with "large-bodies", e.g. the Space Station, special attention should be given to the interactions between a variety of structural appendages mounted on the large body with the environmental plasma. Body parameters which are relevant to appendages are not necessarily the same as those representing the entire large-body. An example which illustrates that, is the parameter known as the "normalized body-size' (i.e., the ratio of the characteristic length of the body to its local Debye length). This parameter may be of the order of 10^3 - 10^5 for the entire large body and be of the order of 10 for specific appendages, each of which creates its own disturbance. And it is not obvious that the overall disturbance created behind the large body is a simple linear superposition of all the smaller disturbances.

As mentioned above we will focus on the wake region and on the (wake/ram) current ratio. It is therefore appropriate to state here that the wake region is the most structurally complicated region around the body. In this region plasma waves are excited, rarefaction waves (or: shocks) propagate, plasma instabilities are generated, wave-particle interactions take place and turbulent zones as well as potential wells exist. In principle, such phenomena are to be expected, since in the wake region, plasma beams collide, ion fronts propagate and strong density gradients exist at the body-plasma interface (e.g., Samir et al., 1983; Singh and Schunk, 1982, 1983; Gurevich and Meshcherkin, 1981a,b; Stone, 1981a,b,c; Al'pert, 1983).

Since the 1960's and particularly during the past decade, experimental and theoretical investigations regarding body-plasma interactions have been performed. The experimental effort consisted of: (1) using in situ measurements in order to investigate the angular distribution of thermal electrons and ions in the near vicinity to satellite's surfaces, (e.g., Samir et al., 1986a,b,c; Samir, 1981; Samir et al., 1979a,b,; Samir et al., 1973, 1975); (2) laboratory studies (e.g., Stone et al., 1981, 1978; Stone, 1981a,b; Hester and Sonin, 1970a,b,; Fournier and Pigache, 1975; Shuvalov, 1979, 1980, Chan et al., 1985, 1986) with applications to interplanetary and terrestrial phenomena. More recently, laboratory experiments were performed in the context of examining phenomena and physical processes relevant to the "expansion of a plasma into a vacuum" (e.g., Wright et al., 1985, 1986; Chan et al., 1984, Chan, 1986; Eselevich and Fainshtein, 1979, 1980, 1981; Raychandhuri et al., 1986). This latter subject will be discussed below. The theoretical effort devoted to study satellite-plasma interactions is by far more extensive compared with the corresponding experimental effort. Among the many papers published we cite: Gurevich et al., 1969; Gurevich et al., 1973; Gurevich and Pitaevsky, 1975; Al'pert, 1983; Parker, 1976, 1977, 1983; Kunemann, 1978; Grabowsky and Fischer, 1975; Liu, 1967, 1969; (Katz et al., 1985, 1984, 1979).

Generally speaking, the theoretical study of body-plasma interaction focuses on self-consistent solutions of the Vlasov-Poisson equations written for electrons and ions. As is known, solutions to the above equations under realistic conditions are not easy to obtain. Hence, simplifying physical assumptions are employed. However, the validity and ranges of applicability of some of the major simplifying assumptions have not yet been adequately tested. As could be expected, the major difficulties are with the studies which attempt to compute the distribution of charged particles and potential in the wake region.

Recently, the phenomena and physical processes involved in the "expansion of a rarefied plasma into a vacuum" were reviewed (Samir et al., 1983). Possible applications to space plasma physics and particularly to the area of "body-plasma" interactions were discussed. It becomes clear that a variety of wake characteristics can be explained in terms of processes involved in the "plasma expansion" complex (Samir et al., 1983, 1986b; Wright et al., 1985, 1986; Chan et al., 1986; Raychaundhuri et al., 1986; Singh et al., 1986). Without going into much detail, we state that the basic phenomena involved in the "expansion of a plasma into a vacuum" are: (1) the acceleration of ions to velocities which are far above their (thermal) ambient values, (2) the creation of a rarefaction wave which propagates into the ambient plasma at about the ion acoustic speed, (3) the formation of an ion front which expands into the vacuum region, and (4) the creation of strong discontinuities in the plasma parameters, and the creation of plasma oscillations and instabilities over certain spatial zones in the "vacuum" (e.g., wake) region.

It is interesting to note that the phenomena involved in the expansion of a plasma into a vacuum, particularly the acceleration of ions, the motion of ion fronts, and the propagation of rarefaction waves were studied theoretically and, to some lesser extent, experimentally in the last decade, e.g. Gurevich et al., 1966, 1968, 1973; Gurevich and Pitaevsky, 1975; Crow et al., 1975; Holm et al., 1981; Johnson and Lonngren, 1982; Eselevich and Fainstein, 1979. While the importance of such fundamental physical processes was recognized by laboratory plasma physicists, they went unnoticed by the space science community.

We submit that the distribution of charged particles and potential in the wake behind a body moving in a collisionless space plasma, can under certain conditions, be understood in terms of the expansion of a plasma into a void (vacuum) or into a more tenuous plasma (Samir et al., 1983). The application of the "plasma expansion" processes to body-plasma interactions is a significant step toward a unified approach in treating the above interactions.

It is therefore reasonable to predict that in studying the interactions of large bodies such as the space station with its surrounding ionospheric plasma, relevant "plasma expansion" processes will have to be considered.

In this paper we present and discuss some of the most significant results obtained from in situ measurements performed via: (1) small satellites orbiting in the ionosphere and the plasmasphere, and (2) the space shuttle mission STS-3/Columbia. We will emphasize a-priori limitations and technical shortcomings of earlier studies including studies which are now in progress. In this way, problems which need further investigation will become apparent.

2. PRESENTATION AND DISCUSSION OF THE MAIN RESULTS FROM SMALL SATELLITES

Most of the information available at the present time from in situ measurements which is relevant to satellite-ionosphere interactions comes mainly from: (1) the Ariel-I satellite (e.g., Samir and Willmore, 1965, 1966; Henderson and Samir, 1967; (2) the Explorer 31 satellite (Samir and Wrenn, 1969, 1972; Samir et al., 1973, 1975, Troy et al., 1975); (3) the Gemini-Agena 10 mission (Medved, 1969; Troy et al., 1970); (4) the Atmosphere Explorer C satellite (Samir et al., 1979a,b, 1980); (5) the USAF satellite S3-2 (Samir et

al., 1981); and (6) from the Plasma Diagnostic Package-PDP satellite on board the space shuttle STS-3/Columbia (Murphy et al., 1986; Kurth, 1986).

The Ariel I information (Samir and Willmore, 1965; Henderson and Samir, 1967) was exploratory in nature and showed for the first time the existence of a wake zone behind the satellite which is depleted of charged particles. Figure 1 shows the distribution of thermal electrons in the wake of the Ariel I as measured by a probe which was flush mounted on the surface of the satellite. Figure 2 shows the same kind of variation, obtained from a boom mounted probe at a distance of $4R_o$ from the surface of the satellite. This distance (Z) is about ($S \cdot R_o$) from the surface, where R_o = the effective radius of the satellite, and S = ionic Mach number. From Figures 1 and 2 the gradient of the [wake/ram] electron current ratio across a distance $\Delta Z = 4R_o$ along the wake axis can be obtained. The ratio $\left[\frac{I_{e(wake)}}{I_{e(ram)}}\right]$ at $Z \sim R_o$ is of the order of 10^{-2} whereas the same ratio for $Z \sim S \cdot R_o$ is of the order of 5×10^{-1} for a plasma with an ionic Mach number of $S \approx 4$.

From the measurements of the probe mounted on the boom and a spherical ion probe mounted on a stem on the satellite's spin axis, acting in itself as a wake creator, it was possible to obtain the variation of the angular distribution of normalized electron around the main body of the satellite and around the spherical ion probes. Figure 3 shows the normalized electron current $\left[\frac{I_{e(\theta)}}{I_{eo}}\right]$ as a function of the angle of attack for the cases: (a) the boom electron probe scans the disturbance created by the spherical ion probe, and (b) the boom electron probe scans the disturbance created by the main body of the satellite (Henderson and Samir, 1967). From this figure, it becomes clear that the (wake/ram) current ratio depends not only on the ionic Mach number but also on the body size and on the surface potential of the body. The spherical ion probe was biased 6 volts negative with respect to the main body, which in itself was between 0 and 1 volt negative with respect to the ambient plasma. The ratio R_D ($\equiv R_o/\lambda_D$, where: R_o = the radius of the satellite, λ_D = the ambient Debye length) was about 10 for the main body and about 2 for the ion probe. Moreover, the normalized distance (Z/R_o) of the electron boom probe from the center of the main body of the satellite was about 5 whereas the similar ratio (Z/R_o) for the spherical ion probe was about 33. The latter implies that the measurements of I_e were made at different distances downstream from the wake creating bodies. While it is not our purpose here to discuss that study in detail we demonstrate the importance of investigating the disturbances created by specific appendages mounted on satellites. In this specific case, the 'appendage' was the spherical ion probe. Unfortunately, until recently, there was no serious follow-on of such studies. Only in the space shuttle STS-3 mission, was attention given to the study of the wakes due to a variety of appendages located on the orbiter (Siskind, 1983; Siskind et al., 1984; Raitt et al., 1984). Such studies will have to be done when the space station becomes a reality.

The Explorer 31 satellite results enhanced our quantitative knowledge regarding the angular distribution of electrons and ions in the nearest vicinity to the satellite surface. Figure 4, which combines results from the Ariel I, the Explorer 31 and the Atmosphere Explorer C satellite measurements

shows the variation of electron current with angle of attack for several altitude ranges. The variation of $[\frac{I_{e(wake)}}{I_{e}(ram)}]$ with altitude, which can be easily deduced from Figure 4, gives the variation with a mixture of plasma and body parameters. Among such parameters we cite: (1) the ionic Mach number, (2) the normalized body size (R_D) and (3) the normalized body potential ($\phi_N = \frac{e\phi_s}{kT_e}$; where ϕ_s = body potential with respect to the local plasma potential, T_e = electron temperature). However, the information given in Figure 4 does not by itself provide for a scientifically meaningful analysis. What is needed is information regarding the variation of: $[\frac{I_{e(wake)}}{I_{e(ram)}}] = f(\theta,r)$ for specific body and plasma parameters. As will be discussed below, some preliminary investigations in this direction were performed utilizing measurements from the Atmosphere Explorer C satellite (e.g., Samir et al., 1979a,b, 1980) and from the USAF/S3-2 satellite (e.g., Samir et al., 1981). It is unfortunate that no serious attempt was made in the past to launch satellites which had the study of body-plasma interactions as a major scientific/technological objective. It is further unfortunate that the few satellites now planned for future launches do not seem to rectify this situation.

The Explorer 31 studies (e.g., Samir et al., 1973, 1975) also yielded a partial picture regarding the difference between the distribution of ion and electron fluxes for a typical ionospheric satellite in the wake. Figure 5 shows the variation of normalized ion current $\frac{I_{+(\theta)}}{I_{+(ambient)}}$ and normalized electron current $\frac{I_{e(\theta)}}{I_{e(ambient)}}$ in the wake of the Explorer 31 satellite for several altitude ranges. The quantitative difference between $I_+(\theta)$ and $I_e(\theta)$ for a limited angular range is clearly seen.

One of the most significant results from the Explorer 31 satellite was the finding that an enhancement in electron temperature in the near wake exists, i.e. $[T_e$ (wake)] > $[T_e$ (ambient)]. If one considers that $[T_e$ (ambient)] = $[T_e$ (ram)], then this finding implies: $[T_e$ (wake)] > $[T_e$ (ram)].

Some examples depicting the $[T_e$ (wake)] enhancement in the wake of the Explorer 31 satellite are given in Figure 6 (Samir and Wrenn, 1972). Similar results obtained by a different probe on the same satellite were presented and discussed by Troy et al. (1975). Earlier in-situ results from a wake experiment on the Gemini-Agena 10 spacecraft system also depicted a similar result (Medved, 1969; Troy et al., 1970). A similar phenomenon was also reported by Berthelier and Sturges (1967) during a rocket flight. Troy et al. (1975) examined the possibility that the $[T_e$ (wake)] enhancement may be due to geomagnetic field effects. The conclusion of that study was that if such effects are present, they are masked by the stronger effect due to the orbital velocity, i.e. by the 'wake-effect'. This conclusion is in accord with the results shown in Figure 6(c). Based on the Ariel I and the Explorer 31 measurements it was concluded that $[T_e$(wake)]>$[T_e$(ambient)] is confined to the

very near wake zone, i.e. to distances $Z \lesssim S.R_o$. This conclusion is also supported by some laboratory experiments (e.g. Oran et al., 1975; Chan et al., 1986). On the other hand, the results from a cylindrical probe on the Explorer 31 do not show a [T_e (wake)] enhancement (Brace, private communication). The cylindrical probe results refer to measurements performed at a distance of about $Z \approx R_o$ from the surface of the satellite. Hence at the present time, based on in-situ measurements, the [T_e(wake)] enhancement was found only by probes flush mounted on the surface of the Explorer 31 satellite. As will be discussed in the next section, the existence of the [T_e(wake)] enhancement is now also supported by some measurements from the space shuttle (Murphy et al. 1986) and contradicted by others (Raitt et al., 1984; Siskind et al., 1984; Siskind, 1983).

A major disadvantage of most available in situ measurements is that they are confined to the very near vicinity of the satellite surface. Most probes whose data were used were flush-mounted on the surfaces of the spacecraft. In this region conceptual difficulties may arise concerning the exact meaning of [T_e(wake)]. Furthermore, it is possible to argue that when the probes are in the very near wake region, the measured currents are drastically reduced and the sensitivity limit of amplifiers can be encountered. This would result in fewer data points available for temperature determinations. This matter was discussed in detail by Samir and Wrenn [1972] and Troy et al. [1975], and it was concluded that the methods applied in the analysis of the probe measurements are an appropriate measure of the electron energy distribution in the wake. A discussion regarding the meaning of [T_e(wake)] and the reliability of measurements was also given by Illiano and Storey [1974] and by Stone [1981a] based on laboratory simulation experiments. Further laboratory studies regarding temperature in the wake were reported by Intriligator and Steel (1985).

After ruling out an explanation of the [T_e(wake)] enhancement in terms of instrumental effects, both Samir and Wrenn [1972] and Troy et al. [1975] speculated that wave-particle interactions take place in the negative potential well behind the body which results in energization of electrons. Alternatively, it is possible to infer the existence of heating mechanisms in the wake region due to stream interactions and/or instabilities correlated with plasma oscillations and turbulence in the near wake.

Whatever the cause of the enhancement in [T_e(wake)], and whatever the conditions required for its existence, no electron temperature enhancement, known to the authors, has been found for ram conditions on small satellites. We will return to this problem in the next section.

As mentioned earlier, most of the results prior to the mid 1970's focussed mainly on determining the angular distribution of electron current around the satellite at the closest vicinity to its surface. Another deficiency of the early studies is that they were not performed in a systematic parametric manner since the needed ensembles of plasma parameters were not always available.

Since the mid 1970's and particularly due to the studies made using measurements from the Atmosphere Explorer C and the S3-2 satellites, the deficiencies mentioned above were partly relaxed.

The angular distribution of the ions around the Atmosphere Explorer C (AE-C) and around the S3-2 satellite were determined for specific plasma parameter ranges (e.g., Samir et al., 1979a,b; 1980; 1981). Some significant results are shown in Figures 7 and 8. Figure 7(a) shows the variation of $\left[\frac{I_+(\Theta=165^0)}{I_+(\text{ambient})}\right]$ with average ionic Mach number S(AV) in the limited range of $3.5 < S(AV) < 4.2$. Figure 7(b) shows the variation of $\left[\frac{I_e(\text{wake})}{I_e(\text{ambient})}\right] = f(M_i(AV))$ for $M_i(AV)$ in the range 1-16. Figure 8 shows the variation of normalized ion density $\left[\frac{N_+(\Theta = 160^0)}{N_+(\text{ambient})}\right] = f(R_D)$. The latter result based on AE-C measurements (cylindrical probe) gives a quantitative measure of the importance of body size on the (wake/ram) current ratio. This study is a small-scale parametric investigation indicating the way for future parametric studies. It should be noted that the result for $R_D \gtrsim 10^2$ is already of direct interest to the interaction of large bodies with their environmental space plasmas.

Figure 9 gives the variation of $\left[\frac{I_+(\text{wake})}{I_+(\text{ambient})}\right]$ with electron temperature for various values of the ratio $\left[\frac{N(O^+)}{N(H^+)}\right]$. It is seen that the dependence on electron temperature is maximum for $N(H^+) > N(O^+)$ and minimum for $N(H^+) << N(O^+)$. This result was interpreted as being connected to the theoretical prediction of non-interacting streams upon filling in the wake zone (e.g. Al'pert et al., 1983; Stone and Samir, 1981). This issue will be further discussed below.

Recently, low energy ion measurements performed by probes on board the Dynamics Explorer 1 (DE-1) satellite were used to study some aspects of body plasma interactions in a subsonic-transonic plasma flow regime (Samir et al., 1986a). This study focussed on the wake region with particular attention given to the behavior of the (wake/ram) ion current ratio. This study deals with body-plasma interactions in a plasma flow regime not dealt with in the earlier studies. It should be noted that the lower and middle ionosphere are characterized by a supersonic/hypersonic plasma flow regime whereas the upper ionosphere and the plasmasphere are characterized essentially by a subsonic/transonic flow regime. Figure 10 shows the variation of $\frac{I_+(\text{wake})}{I_+(\text{ram})} \left(\equiv \frac{I_+(\Theta = 180^0 \pm 15^0)}{I_+(\Theta = 0^0 \pm 15^0)}\right)$ with ionic Mach number, in the range of $0.46 < S < 2.4$. From this figure it follows that: (1) the ionic species (H^+ and H_e^+) act independently upon filling in the wake, or upon expanding into the wake region, and (2) there are other plasma and body parameters which control $\left[\frac{I_+(\text{wake})}{I_+(\text{ram})}\right]$ besides the ionic Mach number.

The first conclusion was also mentioned when we discussed the results of Figure 8 (see also: Samir et al., 1986a; Al'pert, 1983; Gurevich and Pitaevsky, 1975). The second conclusion was discussed in detail in Samir et al., 1979a,b; 1980; Samir, 1981.

The measurements from the DE-1 satellite were compared with a sample of measurements from the Explorer 31 satellite. Figure 11 shows the variation of $\left[\frac{I_+(\text{wake})}{I_+(\text{ram})}\right]$ with S(AV) for the DE-1 and the Explorer 31 results. As seen, both the DE-1 and the Explorer 31 results display a similar behavior despite the fact that the measurements were performed in two different flow regimes. Details of these and other DE-1 results are given in Samir et al., 1986a.

From the discussion given above it follows that the main results can be grouped as follows:

(1) Results relevant to the variaton of the (wake/ram) current ratio with a group of plasma and body parameters, namely S, R_D, ϕ_N.

(2) Results which indicate the existence of an electron temperature enhancement in the wake.

(3) In addition, from the Ariel I measurements (Samir and Willmore, 1985) it was inferred that density fluctuations exist in specific zones of the wake region, and that such fluctuations are indicative of plasma turbulence in the vicinity of the satellite. However not much attention was given to this finding until recently. Recent measurements from the space shuttle (Siskind, 1983; Siskind et al., 1984; Raitt et al., 1984; Murphy et al., 1986) revived this issue and its importance is now well recognized. However, we consider the turbulence discussed by Samir and Willmore (1965) and by Murphy et al. (1986) not to be identical to that discussed by Siskind et al. (1984) and by Raitt et al. (1984).

In summary, the main deficiencies and shortcomings of the studies discussed above are: (1) no systematic parametric investigations under a wide range of parameters were performed, therefore, the available information is fragmentary; (2) most of the studies performed so far are limited to the very near vicinity of body surfaces; and (3) the available information is meagre. This is so, since no attempt was made in the past to study in-depth the body-plasma interactions. This is not the case for spacecraft charging which was studied quite extensively. These main shortcomings do not allow yet for more in-depth studies regarding the physical processes and the main phenomena involved in body plasma interactions. These comments indicate the research avenues to be persued in future studies.

3. THE MAIN RESULTS OBTAINED SO FAR FROM THE SPACE SHUTTLE

The advent of the space shuttle with its wide range of capabilities provides an opportunity to perform controlled and carefully conceived in situ experiments of body-plasma interactions. The technology now developed for advanced missions offers opportunities not available in the past two decades of space exploration. The advantages of using space shuttle and space station capabilities such as tethered satellites, small throw-away detector packages (i.e. small satellites or "free flyers") and diagnostic packages (i.e. small satellites) mounted on remote manipulator arms significantly enhances the potential of body-plasma interaction studies. Such capabilities, used in a controlled manner, will enable the investigation of spatial regions (around

the bodies) which could not have been studied in the past. Furthermore, the availability of the space shuttle and the space station allows experimentation with the shuttle orbiter acting as a near-earth plasma laboratory. Detailed discussions regarding this experimental approach are given in Samir and Stone (1980).

It should be clear that a preliminary stage, preceeding an extensive scientific and technological study-program which utilizes the space shuttle in the above mentioned manner, should be concerned with the quantitative determination and the understanding of the interaction of the shuttle-orbiter with its environment. In fact, this stage is now in progress. Overviews regarding large vehicle-environment interactions (referring to the space shuttle) were given by Raitt (1986) and Kurth et al. (1986), representing the experience already gained by the Utah State/Stanford University and Iowa University teams, respectively (see also Samir et al., 1986c). Preliminary results obtained via the space shuttle mission STS-3 will be discussed below. They will be presented via comparison with the main results discussed in section 2.

Three groups of space shuttle results will be discussed. The first, represents the main results obtained from the measurements performed by the Utah State/Stanford University team (e.g., Siskind, 1983; Siskind et al., 1984; Raitt et al., 1984). The second represents the main results obtained from the measurements performed by the University of Iowa team (Shawhan et al., 1983, 1984 a,b; Murphy et al., 1986). The third represents the main results obtained from measurements performed by the NASA/MSFC team (Stone et al., 1983; 1986).

The results from the experiments done via the space shuttle by the above teams will be discussed in a similar manner to that of section 2. Namely, (1) the wake/ram current ratio, (2) the electron temperature in the wake and in the ram, (3) the turbulence (or density fluctuations) in the vicinity of the body, and (4) the existence of secondary ion beams in the vicinity of the body.

<u>The results for the (wake/ram) current ratio:</u> Very significant depletions in the ion and electron currents in the wake generated by the shuttle orbiter and by structural appendages were found. A result obtained by the Utah State/Stanford University team (Siskind, 1983; Siskind et al., 1984; Raitt et al., 1984) is shown in Figure 12. The amount of current depletion in the wake (i.e. the ratio $[I_e(\text{wake})/I_e(\text{ram})]$ was found to be of the order of 10^{-4}. Furthermore, Siskind (1983) reported that this value may be just an upper limit. A similar result was obtained by the University of Iowa team (Murphy et al., 1986) and shown in Figure 13. Figure 13 shows the variation of electron density with universal time. From this figure and from the corresponding attitude information (Murphy et al., 1986) it follows that the ratio $\left[\frac{N_e(\text{wake})}{N_e(\text{ram})}\right]$ is of the order of 10^{-3} when the wake is created essentially by the main body of the orbiter. Murphy et al. (1986) state that the three orders of magnitude depletion stated above may be a conservative estimate and in reality the above ratio may as well extend into the 10^{-4} - 10^{-5} range. This result is in agreement with the results of Siskind et al., 1984 and Raitt et al., 1984.

With the aid of the PDP, mounted on the Remote Manipulator System (RMS) arm (located on the shuttle orbiter), it was possible to measure the disturbances created by the orbiter at a distance of about 10 meters above the payload bay. This measurement is already an example showing the utilization of a space shuttle capability (the RMS) not available in the pre-shuttle era. It is worthwhile noting that only once, prior to the space shuttle era, was it possible to obtain the angular distribution of electrons at a distance $Z > R_o$ from the surface of the Ariel I satellite (i.e. Henderson and Samir, 1967).

Figure 14 shows the variation of electron density with universal time for the situation where the PDP was mounted on the end of the RMS arm above the payload bay (Murphy et al., 1986). For this case the wake measurements are those represented by the time interval 1700 to 1720 UT. Compared to the results shown in Figure 13 the electron depletion in the wake here is smaller. Murphy et al. (1986) claim this to be due to the fact that the measurement was taken at a distance of the order of 10 meters from the surface of the orbiter. They furthermore report that the fine structure seen correlates with the self-wakes of the PDP and the RMS (the PDP rotated while on the RMS arm). This case is more difficult to interpret unambiguously since the depletion of electron density observed in the wake is due to a mixture of causes. In any case it is interesting to note that $\left[\frac{N_e(\text{wake})}{N_e(\text{ambient})}\right]$ is of the order of 10^{-2} which is similar to the amount of electron depletion in the wake of small satellites having about the same linear dimensions as the PDP. Note that the PDP is a small satellite with a diameter of about 1 meter, and the diameter of the RMS arm is of the order of 0.3 meters. Despite the similarity to the small body, the result shown in Figure 14 requires further examination.

It is not yet possible to carry out a detailed quantitative comparison between the space shuttle results with those from the small satellites discussed in section 2. However, the greater depletion observed for the shuttle orbiter can be understood, at least qualitatively, in terms of its larger body size (see also Samir et al., 1980).

<u>The results for electron temperature enhancements.</u> In section 2 we discussed the temperature results (see Figure 6) from small satellites and stated that an enhancement in $[T_e(\text{wake})]$ is sometimes observed and that the enhancement is of the order of 30% to 100% above the $[T_e(\text{ram})] \approx [T_e(\text{ambient})]$ values.

Siskind et al. (1984) and Raitt et al. (1984) reported the finding of a very significant enhancement in electron temperature when their probe looked into the ram direction, and no enhancement in $[T_e(\text{wake})]$. This $[T_e(\text{ram})]$ enhancement is about a factor of 3 higher than the expected $[T_e(\text{ambient})]$ at an altitude of about 250 km. The elevated $[T_e(\text{ram})]$ values are considered by Siskind and Raitt to be a measure of heated electrons produced by the interaction of the shuttle orbiter and its environmental ionospheric plasma. It should be noted that such an enhancement has not been found before.

Contrary to the above findings, it was shown by Murphy et al. (1986) that no enhancement in $[T_e(\text{ram})]$ exists. Rather, an enhancement was found in $[T_e(\text{wake})]$. This enhancement is much higher than the $[T_e(\text{wake})]$ enhancements obtained from the small satellites. Figure 15(a) shows the variation of

electron temperature with universal time for the situation depicted in Figure 13 for electron density. It is clearly seen that a very significant enhancement in T_e exists when the probe looks into the wake of the main body of the orbiter. Figure 15(b) shows the variation of electron temperature with universal time for the situation given in Figure 14.

Comparing the shuttle results for $[T_e(\text{wake})]$ with those of small ionospheric satellites, we find that the enhancement in $[T_e(\text{wake})]$ increases with increasing particle depletion in the wake. If the occurence and magnitude of the $[T_e(\text{wake})]$ enhancement is indeed correlated with the magnitude of $[\frac{I_e(\text{wake})}{I_e(\text{ambient})}]$, then the physical processes responsible for such an enhancement, whenever and wherever it occurs should be density gradient related. It should be noted that the results from the laboratory experiment of Oran et al. (1975) and Chan et al. (1986) support the in-situ results of the small satellites. Possible physical mechanisms which may be responsible for the $[T_e(\text{wake})]$ enhancement were discussed in Samir and Wrenn (1972), Troy et al. (1975), and Murphy et al. (1986).

As mentioned earlier, Siskind et al., 1984, report the finding of an enhancement in $[T_e(\text{ram})]$. If this enhancement is real, the question remains as to whether it is restricted only to bodies with surface properties similar to that of the space shuttle. If this phenomenon, however, is universal then many of the in situ measurements performed by current collecting probes on board satellites will have to be re-examined.

In summary, we submit that the issue of existence/non-existence and spatial locations of the $[T_e(\text{wake})]$ and $[T_e(\text{ram})]$ enhancements is an open problem. The $[T_e(\text{ram})]$ enhancement may have negative practical consequences regarding the interpretation and reliability of geophysical in situ measurements.

The results for density fluctuations. Measurements made by the Utah State/Stanford team on the space shuttle/STS-3 have revealed the existence of a high degree of turbulence in a wide spatial region around the orbiter (Siskind, 1983; Siskind et al., 1984; Raitt et al., 1984; Raitt, 1986). Hence, the turbulence found was not confined to the wake region only. Furthermore, it was found that the level of the turbulence increased when the probe was located in the ram direction and is in direct correlation with the plasma density.

Measurements of density fluctuations or turbulence made by the University of Iowa team (Murphy et al., 1986) show the turbulence, in specific frequency ranges, to be largest in a transition zone between ram and wake. Hence, it appears that the spatial location of the turbulence discussed by Murphy et al. (1986) is consistent with that reported by Samir and Willmore (1965) and is inconsistent with that of Siskind et al. (1984). This conclusion however may not depict the overall real situation since the spectral content of the two space shuttle experiments is not the same (Murphy et al., 1986; Siskind et al., 1984). In other words, the magnitude and location of the turbulence observed in the two shuttle experiments are given for different frequencies.

The question of turbulence (or density fluctuations) is important from both the scientific and technological points of view. The understanding of its nature may yield greater insight into special problems associated with the interaction of large bodies with the ionospheric plasma. Therefore further studies regarding the elevated electron temperature, in the wake and in the ram, and the turbulence are needed prior to the onset of the space station era.

The results for secondary ion streams: Measurements made by the NASA/MSFC team (Stone et al., 1983; 1986) are discussed in a companion paper (Stone and Samir) in this volume. Here we state the major result only; namely, the finding of secondary ion streams in the near vicinity of the Orbiter. The origin and acceleration mechanism of these streams are presently unknown.

Some Concluding Remarks

From the discussion given in this paper it follows that our present knowledge regarding the interaction of small and large spacecraft with their natural environment in space is still meagre and fragmentary.

In the past, the studies focused on the analysis of relatively few selected samples of measurements most of which were made by probes flush mounted on the surfaces of the satellites. Only in very few cases was it possible to obtain the disturbances created via spacecraft-space plasma interactions at distances further downstream or upstream of the spacecraft.

Recent results from the space shuttle STS-3 have extended our knowledge regarding the interaction of large space structures with the ionosphere. However, some of the major results concerning the plasma environment are in disagreement. The causes for these disagreements/inconsistencies are not yet known.

It may be possible to treat specific plasma phenomena relevant to the interaction of large structures via extrapolation, in terms of body-size, from the knowledge regarding small satellites. However, such extrapolations are limited to phenomena which are solely body-size dependent. Many other phenomena depend on other technical and scientific parameters.

The space shuttle environment, as we know it at the present time, is by far more complicated than the environment of small scientific satellites. The interaction of the space shuttle orbiter with its environment produced a cloud of outgassed material moving at orbital velocities. Such "contaminated" surroundings are due to a variety of scientific and technological causes. Among them we cite: glow, plasma turbulence, wave generation and oscillation, wake effects which spread to far distances from the body's surface, thruster operations, complex shape of the main body, structural appendages, surface erosion, dumps, induced $\underline{V} \times \underline{B}$ fields, surface charging. All the above complex of causes will exist for larger space structures and some of them will undoubtedly be more intensified.

Hence, the surfaces of the shuttle orbiter and the space station are not adequate for the location of plasma diagnostic probes. Small satellites (throw-away diagnostic packages, free-fliers, etc.) will have to be used.

Their use would be: (1) for studies of large body-environment interactions covering large regions of the "interaction space" around the body, and (2) for scientific and technological space plasma investigations.

We submit that prior to the space station era, in-depth experimental and theoretical investigations regarding the interaction of small and large structures, be conducted. There are various ways to conduct such studies with modest budgets.

The basic stage of such a study program should include in-depth empirical and theoretical investigations supported by laboratory experiments. The empirical-experimental aspect should involve the analysis of available measurements (from small satellites and from space shuttle missions). Such studies should be performed, in as much as possible, in a parametric manner rather than in a morphological one. Such studies would provide for a better quantitative understanding of the basic plasma processes common to a variety of interactions. Computer modeling (i.e., the theoretical aspect) should consider realistic situations and use realistic parameters based on the empirical-experimental results. The laboratory studies should be oriented towards ionospheric/magnetospheric space plasmas. Such an approach was not adopted in the past. Hence, we face problems that could have been solved by now if a real awareness to the problems involved in the interactions of bodies with plasmas had existed.

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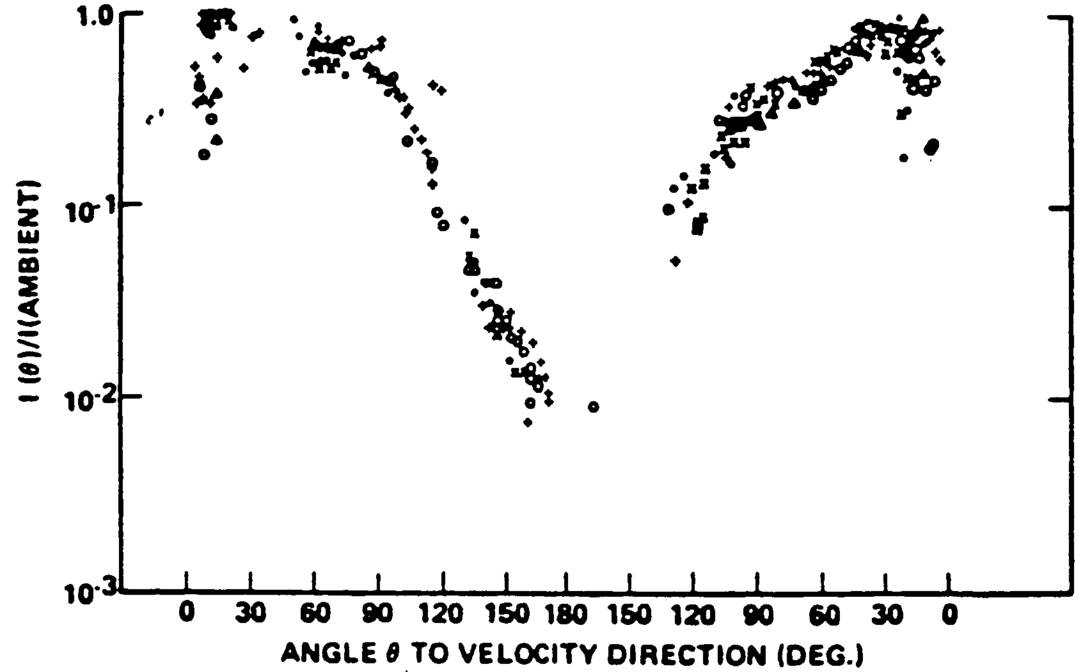

FIGURE 1:

VARIATION OF NORMALIZED ELECTRON CURRENT(I_e) WITH ANGLE OF ATTACK (θ). THE NORMALIZED CURRENT IS THE RATIO OF $I_e(\theta)$ TO $I_{e0}(\equiv I_e$ (AMBIENT)) MEASURED AT Z $\sim R_0$ i.e., AT THE NEAREST VICINITY TO THE SATELLITE'S SURFACE.

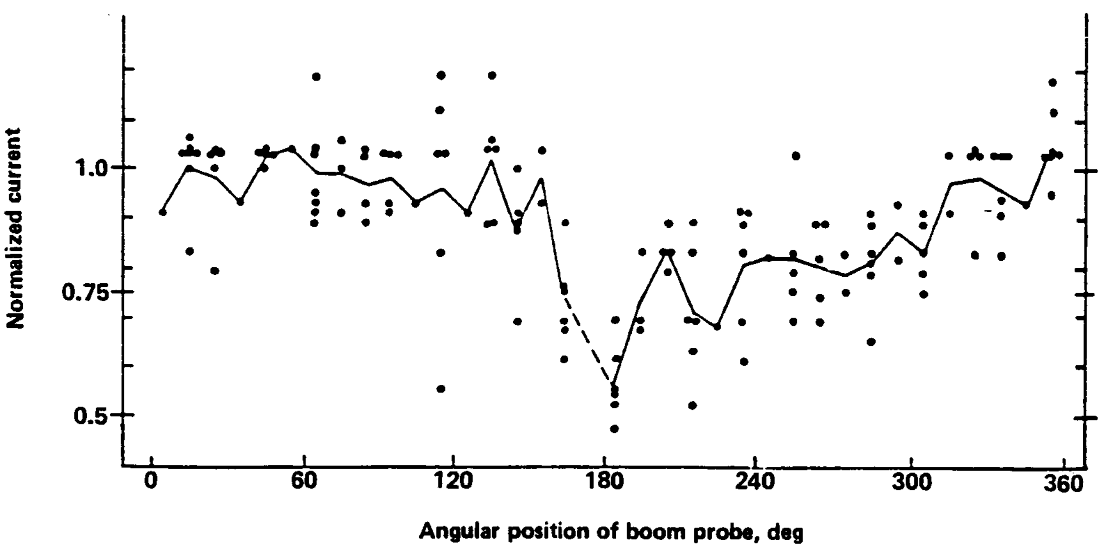

FIGURE 2:

VARIATION OF NORMALIZED ELECTRON CURRENT WITH ANGLE OF ATTACK AS MEASURED AT Z $\approx S \cdot R_0$.

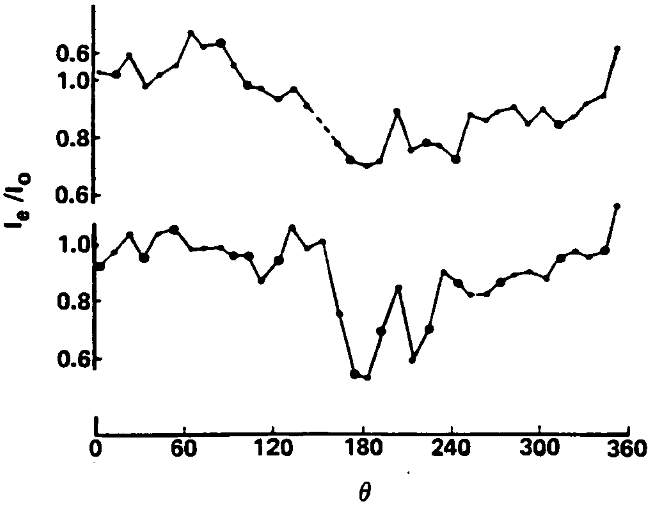

FIGURE 3:
VARIATION OF NORMALIZED ELECTRON CURRENT WITH ANGLE OF ATTACK FOR: (a) THE ION SPHERICAL PROBE AND (b) THE MAIN BODY OF THE SATELLITE.

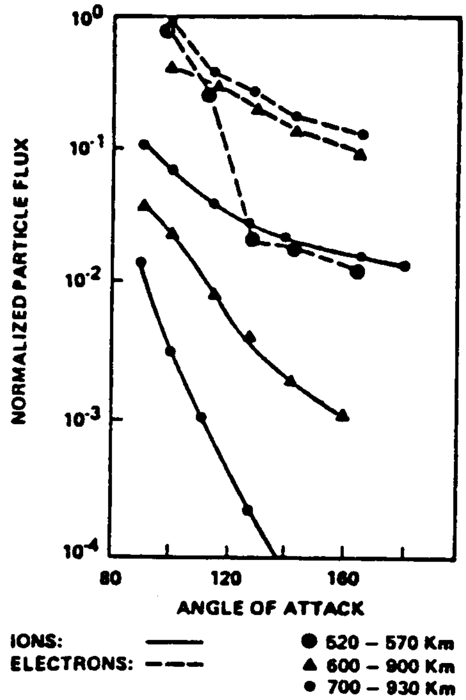

FIGURE 5:
VARIATION OF NORMALIZED ION CURRENTS (SOLID LINE) AND ELECTRON CURRENTS (DASHED LINE) IN THE WAKE OF THE EXPLORER 31 SATELLITE IN THE ALTITUDE RANGES: 520 TO 570 KM (●); 600 TO 900 KM (▲) AND 700-930 KM (•).

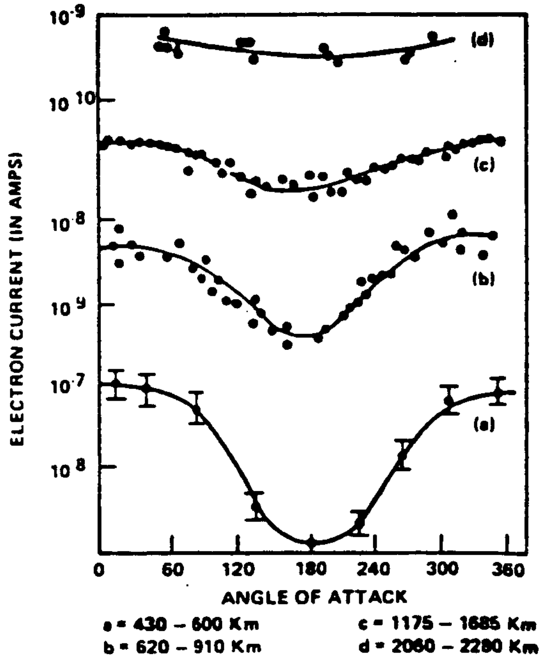

FIGURE 4:
VARIATION OF ELECTRON CURRENT (IN AMPERES) WITH ANGLE OF ATTACK FOR THE ALTITUDE RANGES: (a) 430 TO 600 KM, (b) 620 TO 910 KM, (c) 1175 TO 1685 KM AND (d) 2060 TO 2280 KM, BASED ON ARIEL I EXPLORER 31 AND ATMOSPHERE EXPLORER C MEASUREMENTS.

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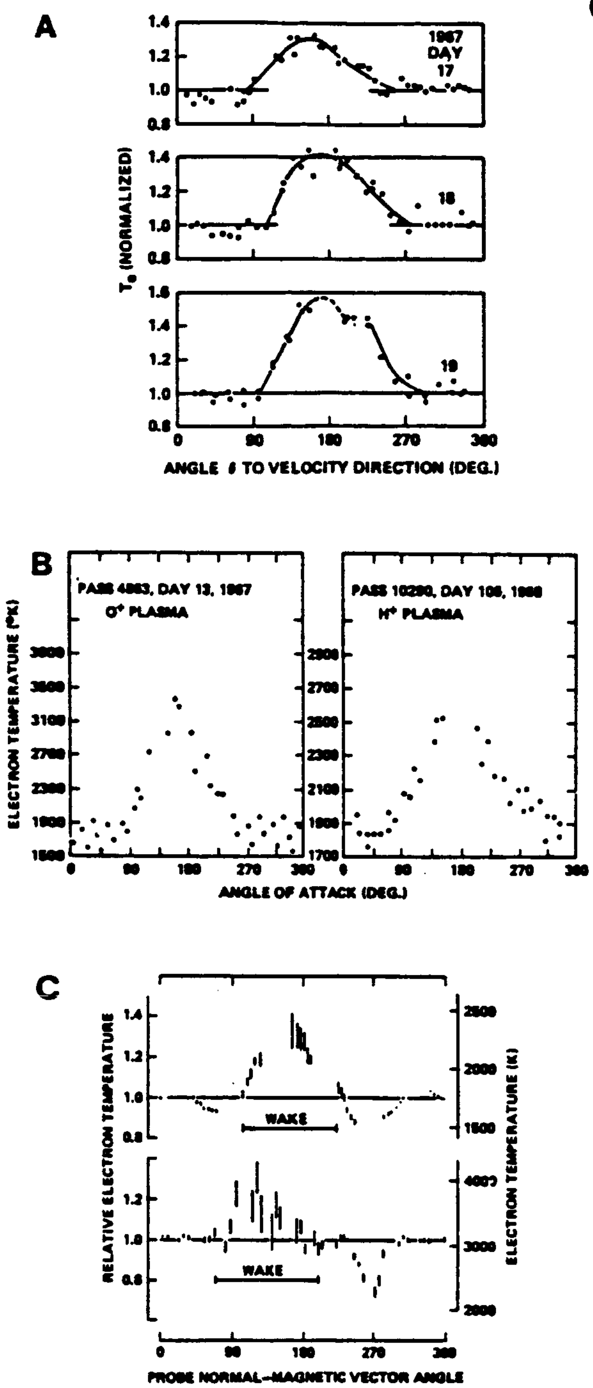
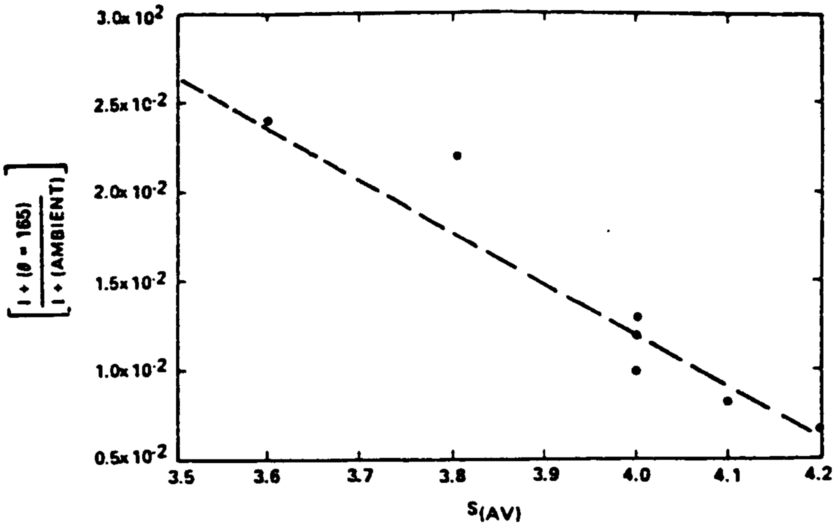


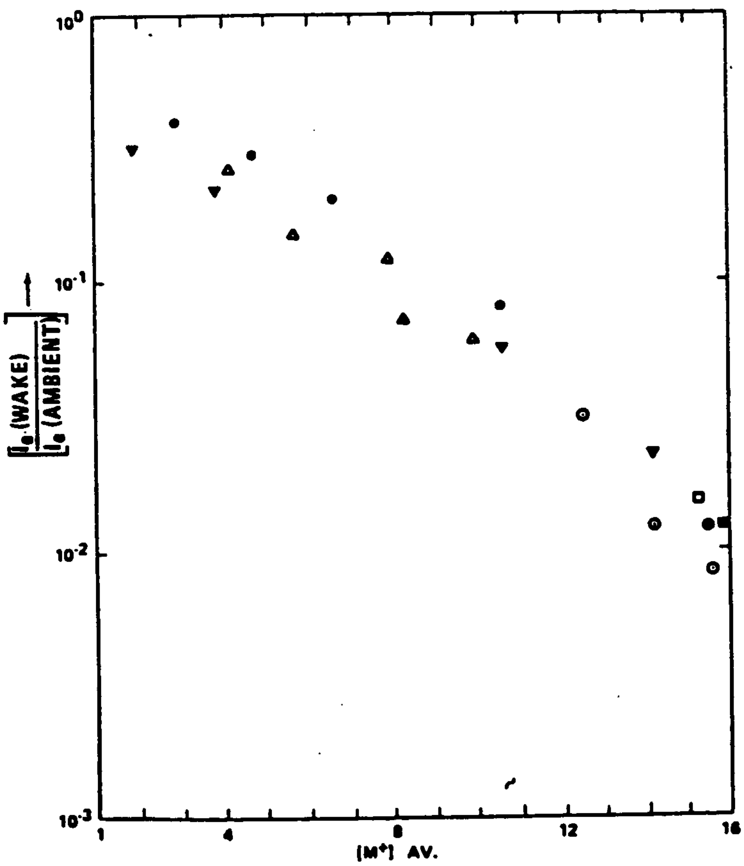
FIGURE 6:

VARIATION OF ELECTRON TEMPERATURE WITH ANGLE OF ATTACK DEPICTING THE T_e (WAKE) ENHANCEMENT.

- **(a)** **[T_e (WAKE)] ENHANCEMENT OBTAINED FOR SEVERAL DAYS AT THE ALTITUDE RANGE 800-900 KM.**
- **(b)** **TWO EXAMPLES SHOWING [T_e (WAKE)] FOR O^+ AND H^+ DOMINATED PLASMAS.**
- **(c)** **WAKE–EFFECT ON T_e OVERTAKES ANY VARIATION OF T_e WITH THE GEOMAGNETIC FIELD.**



(a) VARIATION OF $\left[\frac{I_+ (\theta = 165^0)}{I_+ (AMBIENT)}\right]$ WITH AVERAGE IONIC MACH NUMBER (S(AV)), BASED ON MEASUREMENTS FROM THE EXPLORER 31 SATELLITE.



(b) VARIATION OF $\left[\frac{I_e (WAKE)}{I_e (AMBIENT)}\right]$ WITH M_+(AV) FOR SEVERAL SATELLITE PASSES OVER THE ALTITUDE RANGE 520 TO 1020 KM. EXPLORER 31 MEASUREMENTS.

FIGURE 7

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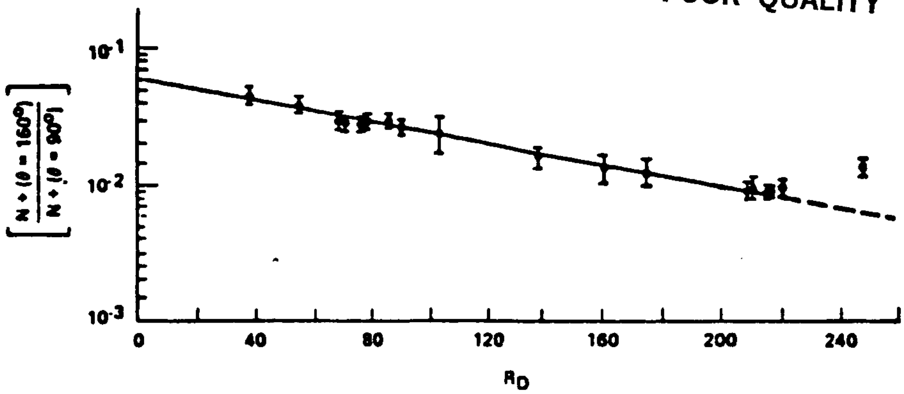


FIGURE 8:

VARIATION OF $\left[\frac{N_+ (\theta = 160^0)}{N_+ \text{(AMBIENT)}}\right]$ WITH NORMALIZED BODY SIZE R_D, BASED ON MEASUREMENTS FROM THE ATMOSPHERE EXPLORER C SATELLITE.

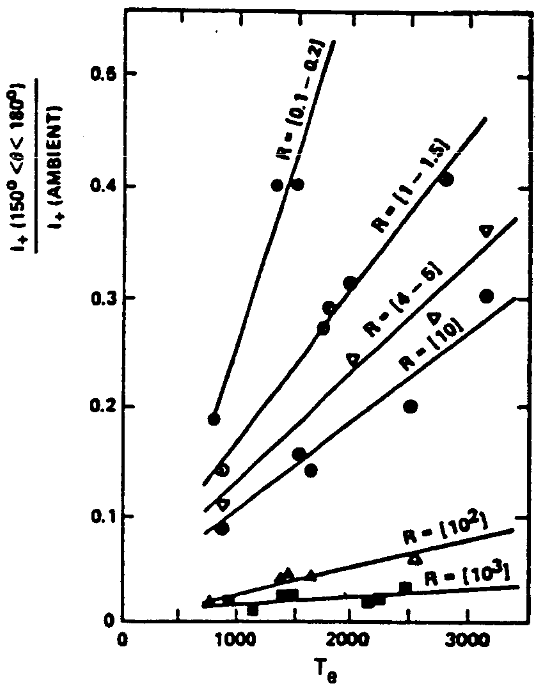


FIGURE 9:

VARIATION OF $\left[\frac{I_+ (150^0 \leq \theta \leq 180^0)}{I_+ \text{(AMBIENT)}}\right]$ WITH ELECTRON TEMPERATURE (T_e) FOR SEVERAL RATIOS OF R = N(O^+)/N(H^+) BASED ON MEASUREMENTS FROM THE ATMOSPHERE EXPLORER C SATELLITE

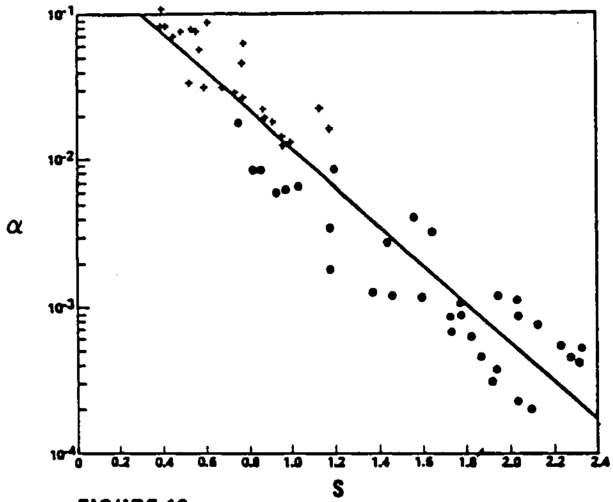


FIGURE 10:

VARIATION OF $\left[\frac{I_+ \text{(WAKE)}}{I_+ \text{(RAM)}}\right] = \left[\frac{I_+ (\theta = 180^\circ \pm 15^\circ)}{I_+ (\theta = 0^\circ \pm 15^\circ).}\right]$

WITH IONIC MACH NUMBER FOR $0.4 \leqslant S \leqslant 2.4$

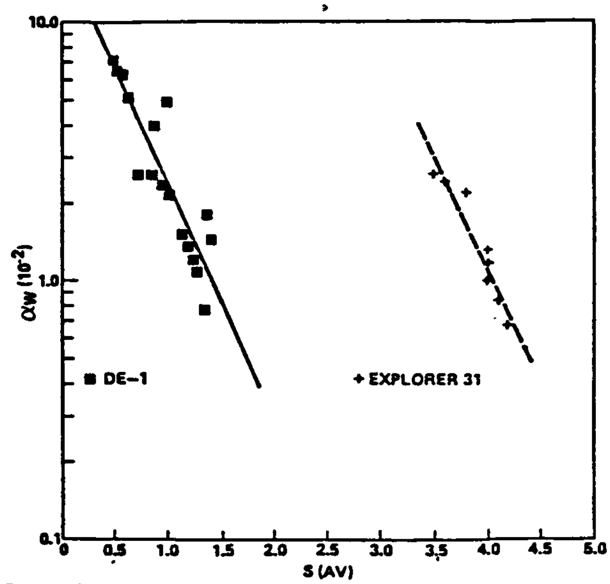


FIGURE 11:

VARIATION OF $\left[\frac{I_+ \text{(WAKE)}}{I_+ \text{(RAM)}}\right]$ WITH S(AV) FOR DYNAMICS EXPLORER 1 AND EXPLORER 31 MEASUREMENTS.

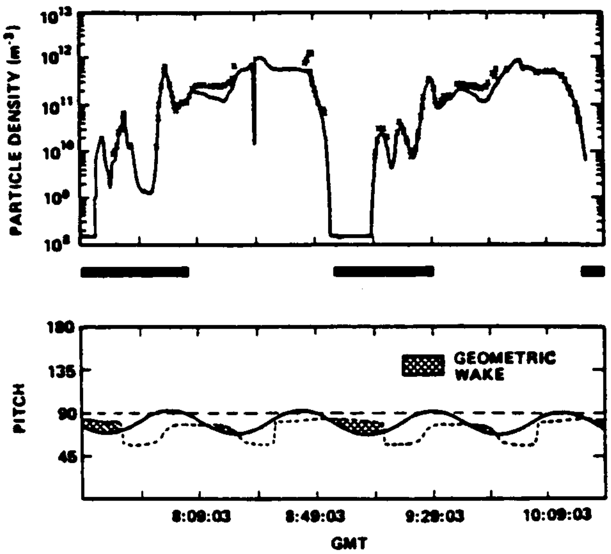


FIGURE 12:

VARIATION OF ELECTRON (SOLID CURVE) AND ION (X) DENSITY WITH CHANGES IN SHUTTLE/ORBITER ATTITUDE. HEAVY BARS BELOW THE TOP PANEL INDICATE NIGHT TIME PERIODS. THE LOWER PANEL GIVES THE TIME INTERVALS FOR WHICH WAKE MEASUREMENTS WERE PERFORMED. AFTER: SISKIND, 1983.

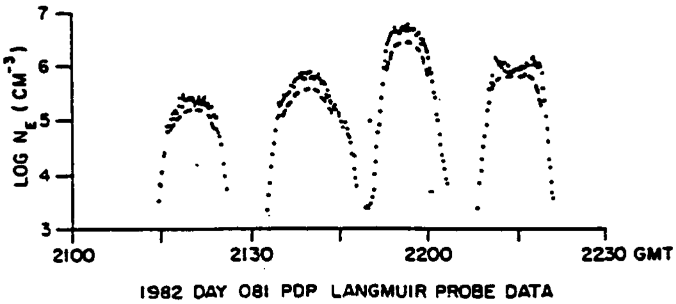


FIGURE 13:
VARIATION OF ELECTRON DENSITY WITH UNIVERSAL TIME FOR THE SITUATION WHERE THE PDP WAS IN THE SHUTTLE ORBITER BAY. HENCE, THE MEASUREMENTS THAT YIELD $\boxed{\frac{N_e\ (WAKE)}{N_e\ (AMBIENT)}}$ ARE FOR THE WAKE CREATED (ESSENTIALLY) BY THE ORBITER. AFTER: MURPHY ET AL, 1986.

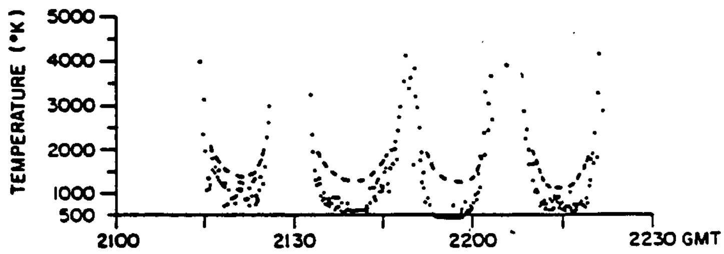


FIGURE 15:
(a) VARIATION OF ELECTRON TEMPERATURE WITH TIME FOR THE SITUATION GIVEN IN FIGURE 13.

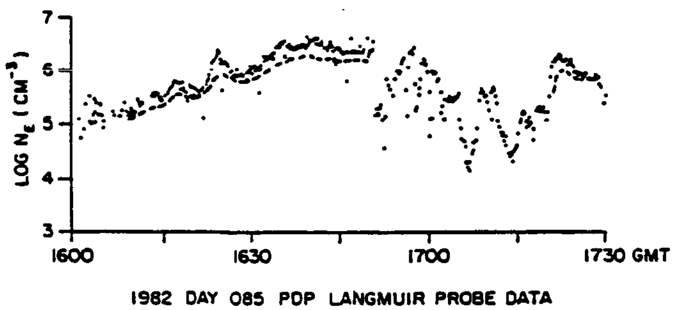
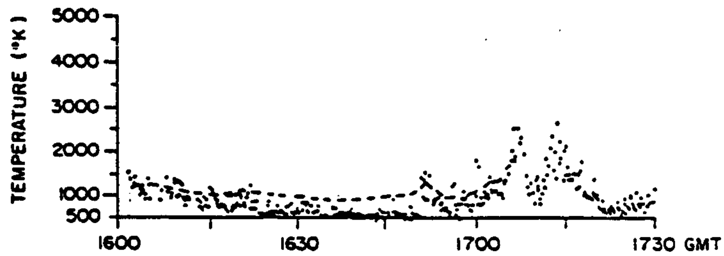


FIGURE 14:
VARIATION OF ELECTRON DENSITY WITH UNIVERSAL TIME FOR THE SITUATION WHERE THE PDP WAS MOUNTED AT THE END OF THE RMS ARM ABOVE THE PAYLOAD BAY. AFTER: MURPHY ET AL, 1986.



(b) VARIATION OF ELECTRON TEMPERATURE WITH TIME FOR THE SITUATION GIVEN IN FIGURE 14.